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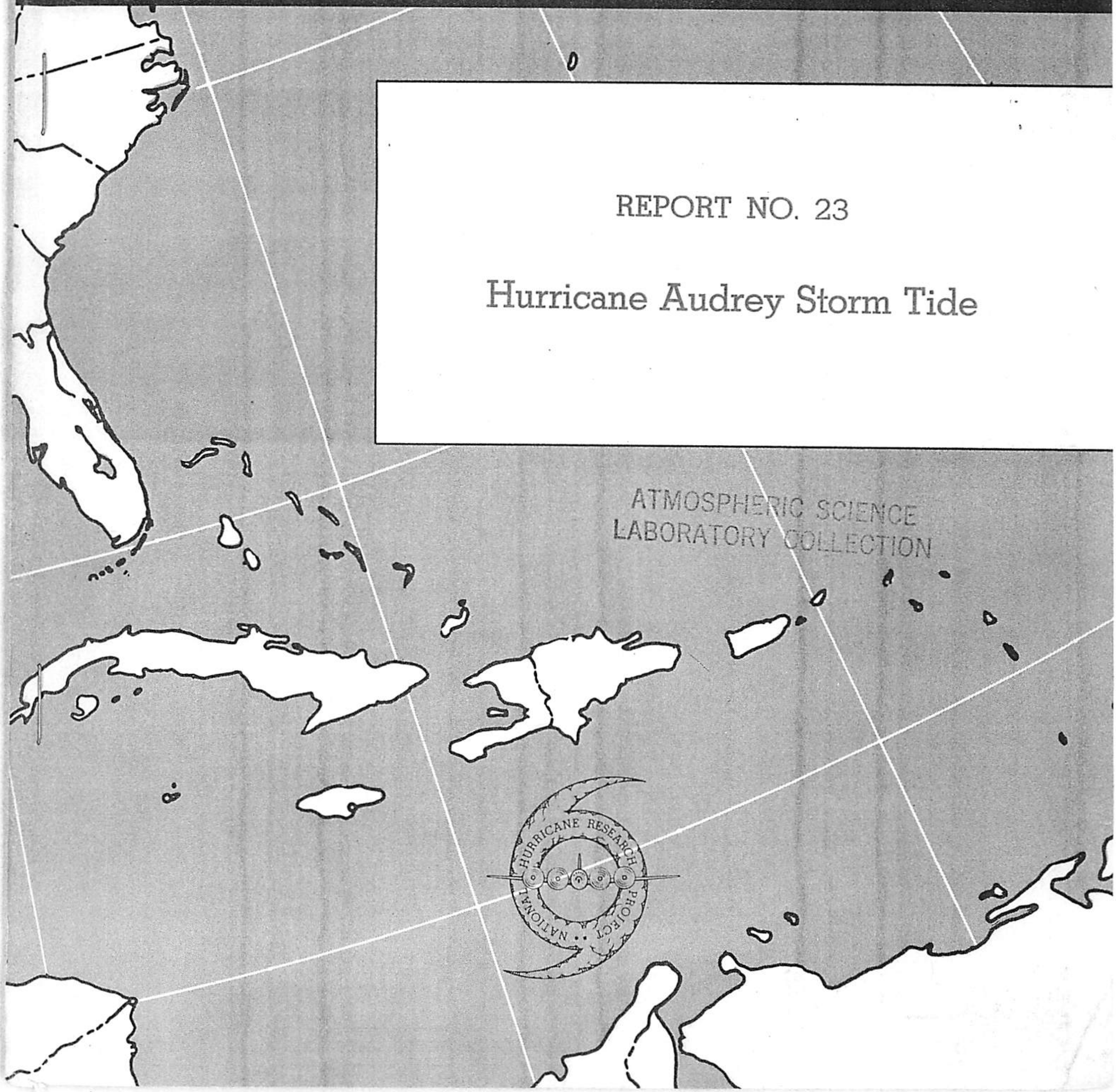

REPORT NO. 23

Hurricane Audrey Storm Tide

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, Secretary
WEATHER BUREAU
F. W. Reichelderfer, Chief

NATIONAL HURRICANE RESEARCH PROJECT

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by
D. Lee Harris
U. S. Weather Bureau, Washington, D. C.

Washington, D. C.
October 1958

NATIONAL HURRICANE RESEARCH PROJECT REPORTS

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HURRICANE AUDREY STORM TIDE

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1. INTRODUCTION

All studies of hurricane storm tides have been severely handicapped by the lack of sufficient observational data to describe uniquely the development of the flood. Hurricane Audrey, which crossed the shore near the Texas-Louisiana border on the morning of June 27, 1957, produced the first major inundation of this type since the organization of the National Hurricane Research Project by the U. S. Weather Bureau, and the development of a nation-wide series of coastal protection studies by the Corps of Engineers under Public Law 71, 84th Congress. As a result of this intensified work by the Corps of Engineers and Weather Bureau, and with considerable support by the Coast and Geodetic Survey and other agencies, more data relative to the storm tides have been collected for hurricane Audrey than for any earlier hurricane.

At the beginning of this study, it was hoped that these data would permit definitive answers to some of the perplexing problems relative to hurricane storm tide generation. Unfortunately, this has not been the case. It is believed that this study has led to a much clearer view of the problems and that this in turn will permit improvement in forecasting, in developing hurricane protection plans, and in collecting more useful data in connection with future hurricanes.

A preliminary report of the wind speeds, rainfall, minimum pressures, high tides, and loss of life and property due to this storm were given in a special weather summary, Weekly Weather and Crop Bulletin [12]. More complete reports of this information and other historical data were given by H. C. Summer [9, 10]. A meteorological discussion of the storm was given by Ross and Blum [8], and a meteorological discussion of the entire 1957 hurricane season by Moore and staff [6]. Graham and Hudson [3] have made an analysis of the detailed wind field in the storm as it crossed the coastline. Morgan, Nichols, and Wright [7] have given an account of the morphological effects of the storm on the Louisiana coast. Many additional manuscripts and working papers dealing with the various aspects of this storm have been prepared by several different organizations and given limited distribution. Some of these will undoubtedly be published for general distribution in the future. Several have been consulted in the process of preparing this manuscript. References are not being made to these unpublished manuscripts as this will not improve the documentation and most of the data available from one unpublished source were available from several. Because of the large volume of data available on other aspects of this storm, this paper will be restricted to a discussion of the high tides and other data directly related to the high tides.

2. DEFINITIONS

It is desirable, in this report of inundation of coastal areas by hurricane Audrey, to use rather precise definitions of several terms in common usage. In the interest of clarity these definitions are collected below. The reasons for using these particular definitions will be made clear in the following pages.

TIDE - The still-water level as measured in a stilling well or any other vessel or basin whose shape is such as to eliminate the rise and fall of the water surface with periods of only a few seconds.

STORM TIDE - The observed tide as affected by a storm. The storm tide may occur in basins not normally affected by the tide, and even on land which is normally dry.

PREDICTED TIDE - The tide as predicted by tide prediction agencies such as the Coast and Geodetic Survey and published in official Tide Tables. The predicted tide takes full account of the gravitational attraction of the sun and moon, and closely approximates the average seasonal variation in sea level as determined from a long series of records.

STORM SURGE - The difference between the storm tide and the predicted tide as corrected for secular changes and anomalous seasonal variation in sea level.

OBSERVED HIGH WATER - The maximum point on a continuously recorded tide grapn as smoothed to eliminate perturbations with periods of less than one hour.

EXTREME HIGH WATER - The maximum point on a continuously recorded tide graph without smoothing.

MAXIMUM STAGE RECORDER - A small tide gage designed to indicate the highest tide occurring since the last resetting of the instrument.

HIGH WATER MARK - A debris line left inside a building or other basin with a restricted opening which will permit the free flow of the tide but which will dampen most of the variations in water surface elevation due to short-period waves.

3. STORM TIDE RECORDS

A. Time History of the Storm Tide. Figure 1 shows the observed storm tide at more than 30 recording tide stations affected by hurricane Audrey. These graphs have been plotted from hourly readings from the continuously recorded tide graphs. This was necessary in order to reproduce data from a wide range of chart scales on a common basis for visual comparison. The effects of oscillations with periods of less than one hour cannot be determined from the record. The extreme tide heights have been shown in all cases. Photographs of some of the original records, showing the short-period oscillations will be given later.

These records have been divided into a number of panels, each showing the behavior of the storm tide in a different waterway. All records in each panel have been referred to the same time axis, with the date given at noon for each day. All records are given in Central Standard Time. The height scale is also the same for all records and is given in the lower left hand portion of the figure, but the zero of the height scale has been adjusted for each station to avoid overlapping curves. The extreme high water due to the storm tide is shown for each curve unless the gage became inoperative before the extreme high water was reached. The extreme high water at a few stations resulted from rainfall runoff, and in these cases an effort has been made to indicate the peak water level due to the storm tide.*

All tide elevations have been reduced to mean sea level values. However, the period of record used in determining the mean sea level is, in general, unknown to the writer. The uncertainty in comparing the records of adjacent tide observations due to this cause is of the order of 0.5 ft. in this region of land settlement and rising sea level.

Hourly positions of the storm center, as determined by a post analysis of all pertinent data by the Hydrometeorological Section of the Weather Bureau [3] are shown by a dashed line from south to north across the figure.

Records were obtained for three stations near Galveston, Tex., and one at Morgan Point in northwestern Galveston Bay, and one on the Intracoastal Waterway between Galveston Bay and Sabine Lake, close enough to the southern end of the canal to suggest that it reflects conditions in East Bay. (These are labelled E through I.) At all three stations near Galveston the water level increased due to the storm while the storm was southeast of Galveston and the wind was blowing from land to sea. If only these data were examined, it would appear that some dynamic effect was causing the storm tide to rise against the winds of the hurricane. This may be true, but the out of phase relationship between the records at Station E (High Island) and F (Morgan Point) and records for stations near Galveston (G, H, and I) suggests that the high tide near Galveston was due to a transport of water from the northern portion of the bay to the Galveston area by the northerly winds which blew over the bay during the period of rising tides. Because of the short duration and high speed of these winds it is unlikely that all of the water carried from the northern portions of the bay was able to escape through the entrance of Galveston Channel as fast as it was carried southward by the wind. The release of this mound of water, as the winds decreased in intensity and shifted toward the southwest after the passage of the storm, did induce a secondary oscillation as shown by the second peak in the afternoon of June 27 at stations G, H, and I. The peak at station E probably resulted from the first portion of this oscillation. This oscillation could have led to some flooding all around the bay even without any increase in the amount of water in the bay.

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*I am indebted to the U. S. Army Engineer District, New Orleans, La. for this determination.

The record from Morgan Point, F, supports this hypothesis. A time history of the water level during the storm from the northern shore of Trinity Bay, and for the tides on the open coast of Galveston Island would be useful. A tide gage was activated on the Gulf side of Galveston Island shortly after hurricane Audrey.

It is difficult to apply a similar explanation to the record for the vicinity of Freeport, stations A,B,C,and D. Here it appears that some rise in sea level must have occurred on the open coast but this may have been modified by resonance or convergence in the channels. Information on the height of the storm tide at locations with a direct exposure to the open sea is needed to be sure of this.

Although the tide gage near Cameron, station N, was destroyed by the storm, a portion of the record was reconstructed from the log of the nearby Coast Guard station on Monkey Island, and is shown as a dashed line in the figure. Other data were obtained from eye witness accounts. The tide was abnormally high on the coast south of Cameron and more than 130 people had evacuated their homes to the court house by midnight. By 0200 the water was in the streets of Cameron. By 0245 it was above the running boards of automobiles in the court house square. By 0430 the water was waist high in some streets of Cameron.

The records for stations M,L, and K, farther inland, show that the tide did not become abnormally high at these locations until after 0300. The time of the peak water level was also progressively delayed as the distance from the open coast increased.

At Creole, about ten miles east of Cameron and a half of a mile farther inland, indicated by an asterisk on this map, eye witness accounts report that the roads, elevation about 6 feet, were still passable at 0500, but became impassable by 0600. The peak water levels observed in Creole were higher than in Cameron, and the peak reported storm tide from this hurricane occurred about 3 miles east of Creole.

The water level records for the Mermentau River, stations O through S on the map, closely parallel the records for the Calcasieu River. The fragmentary record for station S supports the reports of abnormally high water on the coast by midnight.

The record for Pecan Island, station T, is especially interesting. The gage is located on a canal leading to White Lake, and is on the north side of a ridge which varies from 7 to 9 feet in elevation in this vicinity. Here the water level dropped until 0800 and then rose rapidly to an elevation of 6.9 feet by 1100. The water level increased more than 6 feet between 0800 and 1000.

A comparison between the tide recorded several miles from the coast, and on a coastal island is shown at the extreme right side of figure 1. Station l is located on an oil drilling platform of the Humble Oil Company. Station k is located about 10 miles away on the northeastern tip of Grand Isle, La. These stations were on the periphery of the storm, and may not be representative of conditions near the center of the storm. However, it is noteworthy that the effect of the hurricane on sea level was much greater at Grand Isle on the coast than at the oil platform in open water.

The other sets of records indicate the same general features, a progressive delay in both the onset and peak of the storm tide as distance from the open coast increases, and will not be discussed in detail.

B. Extreme Storm Tide Elevations. Figure 2 shows the extreme storm tide elevations at more than 100 locations in Louisiana and Texas. Variations in the extreme tide elevation amounting to several feet in a distance of less than one mile can be noted at several locations on the map. It is believed that these differences near the coast are due principally to local variations in exposure to wind and waves. Farther inland the variations are apt to be due to the presence of control structures, the higher values being reported on the seaward side of dikes and levees. At many places, the spoil banks resulting from canal dredging formed levees which impeded the flow of the storm tide. The water level on nominal dry land was often higher than that in nearby canals for several days after the storm. The shaded area on this map indicates the limit of widespread inundation as taken from a report prepared by the New Orleans District of the U. S. Army Corps of Engineers.

These data have not been analyzed to show specific depth of flooding contours, because it is believed that such an analysis would imply a degree of regularity not present in nature.

4. EFFECTS OF LOCAL TOPOGRAPHY

To understand the variations in peak water level and in the timing of the storm tide, it is necessary to consider the topography of the region affected. This is illustrated in figure 3, based on the latest available U. S. Geological Survey Topographic Charts. The figure shows the major topographic features in the region most severely inundated by this storm. The coastline in southwestern Louisiana consists of narrow ridges frequently no more than 100 feet across and less than 3 feet above mean sea level. North of this ridge, the land quickly drops to approximately sea levelor below. In may locations the first continuous 5-foot contour is 15 to 20 miles inland from the coast. Several other ridges with elevations varying from 2 to 10 feet are found more or less parallel to the coast. Representative elevations are shown at intervals along the ridges.

It appears that the easterly wind ahead of the storm, drove the water from the eastern end of White Lake and produced the fall in water level at the Pecan Island gage. Later, as the water south of the Pecan Island ridge became high enough to flow over the ridge, the water level at this gage rose rapidly to approximately the height of the ridge. It could not go much higher because the large pond north of the ridge would have to be filled to support any higher elevation.

The 10.9 foot storm tide reported south of the ridge may have been due to a perturbation in the flow, formed because of the presence of the ridge.

The same sequence of events appears to have been followed near Cameron and Creole. The ridges south of Cameron were lower. Both the center of the storm and the maximum wind speeds were nearer. This led to higher tides on the open coast. Consequently the ridges were topped earlier than at Pecan Island. The ridge south of Creole is higher than that south of Cameron, and this appears to account for the delay in the development of serious flooding, and perhaps for the higher peak tide elevation ultimately observed. This hypothesis can also explain the many eye witness reports of tidal waves at inland locations.

5. SEA LEVEL, TIDES, AND LAND ELEVATIONS

The regular rise and fall of the sea surface around the mean value for the day are results of the gravitational attraction of the sun and moon on the waters of the earth. This force can be computed accurately many years in advance. The response of the sea to this force at any particular place can be also predicted with a high degree of accuracy if observations covering a period of 369 days or longer are available to serve as a basis for the predictions. Useful predictions can be made with as few as 29 days of record. An example of such predictions for the region affected by hurricane Audrey for the period June 25 through 29 is given in figure 4. The predictions for Timbalier Island are based on 29 days of record. The others are all based on more than a full year of record. The peak storm tide occurred between Eugene Island and Galveston and it is presumed that the tides shown for these stations are characteristic of the normal tides in this area on the day of the storm. Notice that the tide curves are nearly flat and near the daily maximum at the time of the peak storm tide. These curves were plotted from hourly tide predictions made on the IBM 704 electronic computer at Suitland, Md. and were based on harmonic constants furnished by the Coast and Geodetic Survey.

The mean level of the sea for any day also varies with seasonal influences and meteorological conditions. Even without hurricanes the range in tide level in the western Gulf of Mexico due to meteorological conditions is far greater than the range due to astronomical factors. Figure 5 shows the variation in daily mean sea level for the months of May, June, and July at several tide stations affected by hurricane Audrey. All data here are referred wherever possible to the geodetic mean sea level of 1929 as used on topographic maps. An asterisk is used to indicate those stations which have not been referred to the geodetic level net, and at which a locally determined mean sea level has been used.

It is evident from this figure, that the actual sea level was found to be 1.0 to 1.5 feet above the mean sea level,* as indicated on most maps, for several days before the storm and over a region much larger than that seriously affected by the hurricane. Thus, it must be assumed that so far as effects

*A more accurate determination of the mean sea level during this period could be made by considering the weighted means of hourly tide heights as described by Groves [4] and Doodson [2]. However, it is believed that for the purposes of this study the slight increase in accuracy obtained by this method would not be worth the extra work involved.

due to the hurricane are concerned, the land elevations were actually about 1.0 to 1.5 feet below the values indicated on maps of the area during this storm. Even a quick look at figure 3 will show that this is not a trivial change in this area.

It is important to know how often discrepancies of this magnitude between the official and the actual sea level occur. Information on this question is provided by figure 6. The observed monthly mean sea level at several tide stations in the western Gulf are shown by solid lines, and the predicted values based on the constituents of the annual and semiannual tide are shown by dashed lines. Both curves are referred to the geodetic mean sea level wherever possible.

The separation between the two curves at Galveston requires some explanation. A tide gage can do no more than measure the height of the water surface relative to the land, it cannot measure the absolute height of either. The tide gage at Galveston is one of the oldest in the western Gulf of Mexico. The period 1909-1927 was used in determining the local mean sea level of Galveston for use in tide predictions and an even earlier period (December 1, 1903-November 29, 1906) was initially used in establishing the geodetic level net. This is now known to have been an unfortunate choice, for the land surface at Galveston is now known to be sinking at a significant rate [5]. The elevations assigned to the geodetic bench marks in Galveston at the present time are based on levels from the interior of the country completed in 1954 [11] and are lower than those obtained from earlier surveys. There is also evidence of an increase in sea level along the entire eastern and Gulf coast of the United States which is not due to land subsidence [1]. We do not know of any method of determining accurately what fraction of this change is due to land subsidence and what to attribute to rising sea levels, but it does appear reasonable that the predictions based on a fixed sea level relative to land should be below the most recent determination of the geodetic sea level in regions of land subsidence, while the actual sea level would tend to lie above the geodetic plane in recent years. The same factors enter into the relation between the other curves but to a lesser extent.

It would be a simple matter to allow for the long period change in sea level elevation relative to the land by adding a datum correction to the predictions for Galveston. This is not feasible because Galveston predictions are used as a basis for inferring predictions at many other ports not subject to the same rate of land settlement as Galveston. Modifying the Galveston predictions without modifying the elevation of the low water datum plane is likely to produce a deterioration in these inferred predictions. The low water datum plane at Galveston is also used as a basis for many hydrographic surveys, in the legal definition of state boundaries, and in the deeds of much valuable private property. Thus, this datum cannot be changed lightly.

Several new tide gages have been installed in this region in recent years and more are planned. This new observational program should lead to an improvement in both tide predictions and the specifications of tidal datum planes in the future.

6. THE STORM SURGE

Figure 7 shows the computed storm surge for those stations whose predicted tides are given in figure 4. The storm surge, as discussed here, is obtained by subtracting the monthly mean sea level and the predicted tide, obtained without the use of seasonal components, from the observed tide. The peak surge values observed at Port Isabel, Tex. and Pensacola, Fla. on June 27 cannot be traced to any direct effects of hurricane Audrey. The table to the right of the hydrographs gives both the observed and the predicted monthly mean sea level. The monthly sea level anomaly accounted for a significant fraction of the total disturbance at all stations. An examination of the available tide records from foreign tide stations in the Gulf of Mexico and Caribbean area suggests that the mean sea level in the entire Gulf of Mexico was above normal in the month of June 1957. The anomaly was greatest along the shores of eastern Texas and Louisiana.

7. ORIGINAL TIDE RECORDS

Most of the preceding discussion has been based on hourly or extreme tide observations. This does not tell the full story, for oscillations with periods much shorter than an hour are frequently apparent in the tide records of a hurricane. Copies of several Coast and Geodetic Survey tide records are shown in figures 8 and 9. These are typical of all the gage records examined. The Coast and Geodetic records were chosen for this display because of their near uniform scale. The left end of the short horizontal marks indicates the hours. Data read at these points have been used in plotting the curves of hourly readings. Hour numbers for even numbered hours are given above the curve. A vertical scale is given on each figure. Figure 8 is a photograph of the original tide gage record for Galveston. This is one of the gages equipped with two recording pencils so as to extend the range over which the tide can be recorded without having to use any reversing mechanism. The second pencil began to record shortly before 0100 and the first pencil went off scale a little after 0200. An oscillation with a period of 20 to 30 minutes is clearly indicated in this record. The extreme high tide of 6.6 ft. m.s.l. occurred, at the peak of such an oscillation shortly before 0500. The high water for the day (used in most tidal analysis), 6.3 ft., was obtained by drawing a smooth curve through several hourly values near the time of the extreme high water.

The records for four stations in Louisiana are combined in figure 9. The recording pencil at Eugene Island went off scale shortly after 0600, came back on scale briefly between 0700 and 0800, and went off scale again after 0800. A new and higher base line was established as the recording pencil returned permanently to the recording position shortly after 1000. The peak tide height had to be inferred from the data on the chart and may be in error by a few tenths of a foot. The short period oscillations seen in the records for Galveston are also apparent in all of the records shown here. If one were to look only at the records for Galveston and other land locked harbors, he might suspect that these oscillations are due to an oscillation of the harbor. However, these oscillations are also present in the records from the Humble Oil Platform. These cannot be due to harbor conditions.

Since these oscillations can occur in open water, it is not safe to regard all such oscillations observed in harbors as being due to conditions within the harbor.

8. CONCLUSIONS

This study shows that even the extensive collection of storm tide data available from hurricane Audrey is not sufficient to permit a detailed reconstruction of the events as they occurred. It is strongly suggested that warning procedures could be more effective if information concerning the tide heights on the open coast were available at proper places inland. This information, in addition to the other information concerning hurricanes, would permit a better estimation of the ultimate storm tide peak. This information, properly related to other hurricane information, should also help the local officials responsible for public safety to determine the seriousness of the situation at an earlier hour, and might justify a forced evacuation, if necessary. Information on the current state of the tide, if promptly available at the right places, should lead to a significant reduction in the loss of life attributable to hurricanes.

9. RECOMMENDATIONS

1. Recording tide gages, in hurricane proof structures, should be established along the open coast in front of all coastal towns whose elevations are less than 20 feet above sea level.

2. These gages should be connected with a remote recorder in an inland location, preferably the Weather Bureau Office, from which information on the existing state of the tide could be related to meteorological information and promptly relayed to all officials responsible for public safety in the threatened area.

3. A series of maps, similar to that shown in figure 3, which will clearly point out the danger from coastal flooding should be prepared for the entire United States coastline subject to this danger.

The Weather Bureau has made a start on the implementation of these recommendations by installing remote tide recorders in several coastal offices and by compiling much of the data needed for maps similar to figure 3.

ACKNOWLEDGMENTS

This study would not have been possible without the extensive cooperation of the U. S. Army Engineer Districts in New Orleans and Galveston; the Coast and Geodetic Survey and colleagues in my office, Charles Vernon Lindsay who prepared most of the figures, Elinor Sharpe, who also assisted in the preparation of the figures and typed many drafts of the manuscript, and N. A. Pore who wrote the code for tide predictions on the IBM 704 and who also contributed in many other ways.

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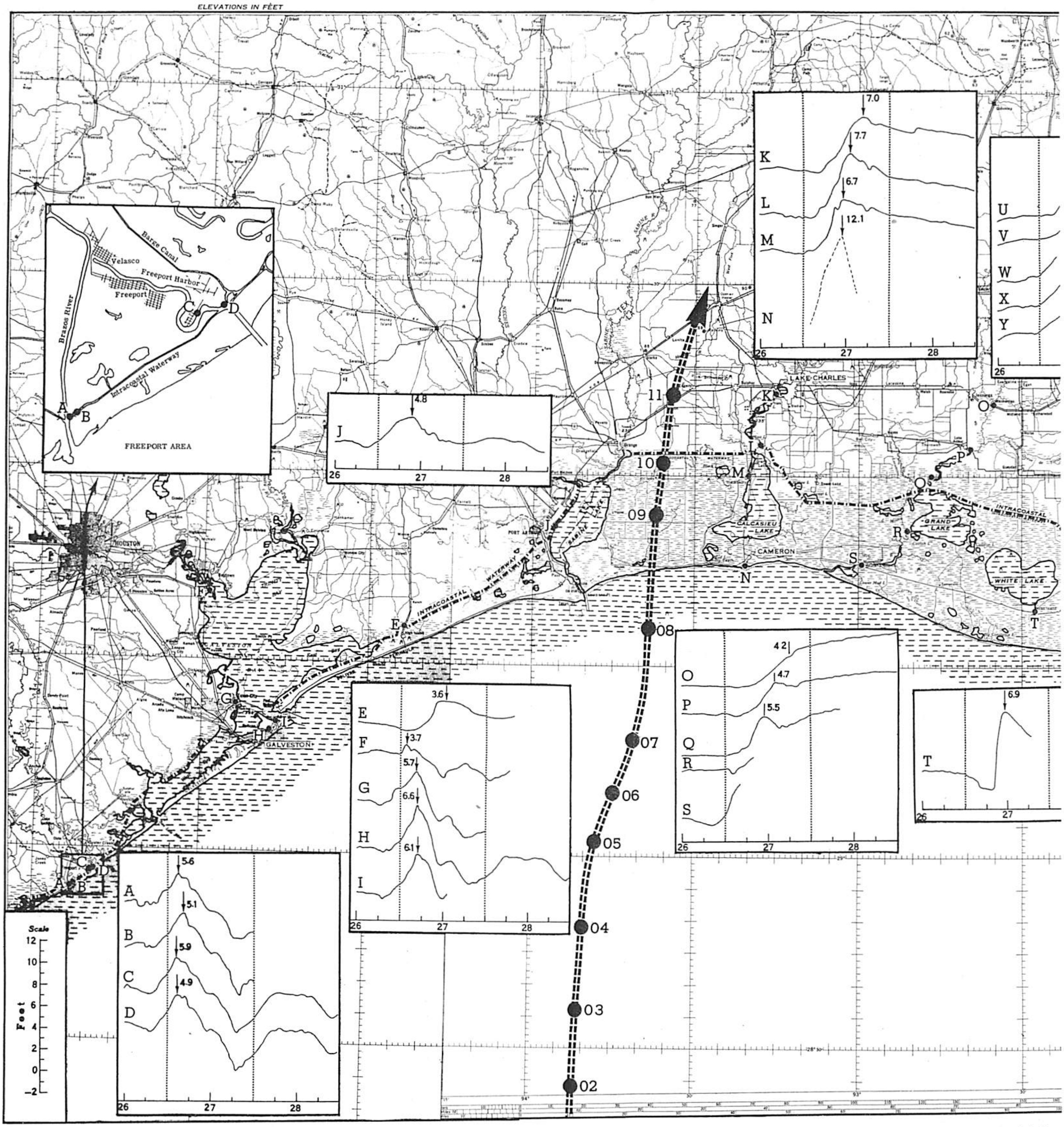
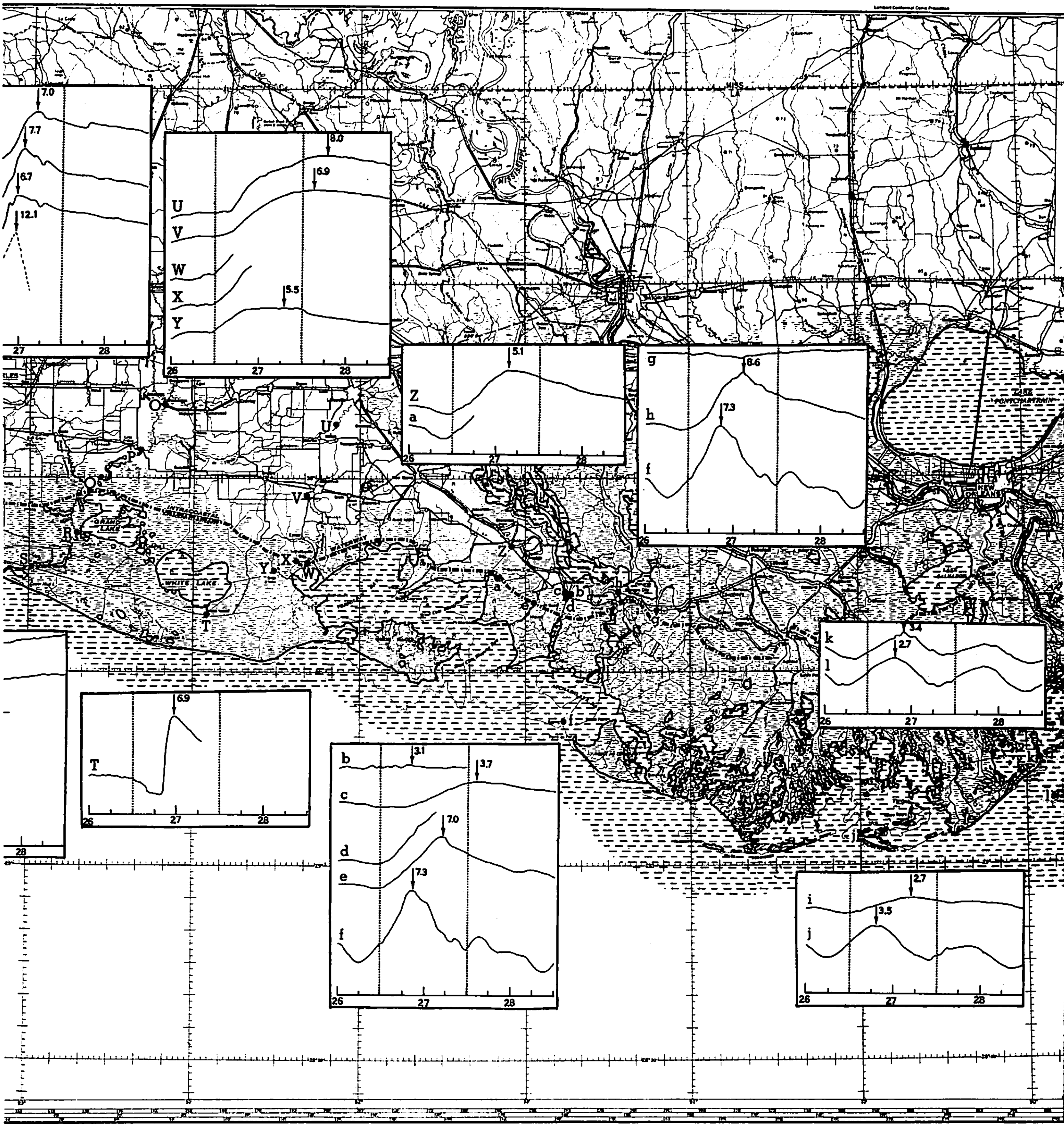


Figure 1. - Graphs of observed storm tide at tide
shown as insets near their location on the map
coasts. Scale is at left. Hourly positions o
shown on track.



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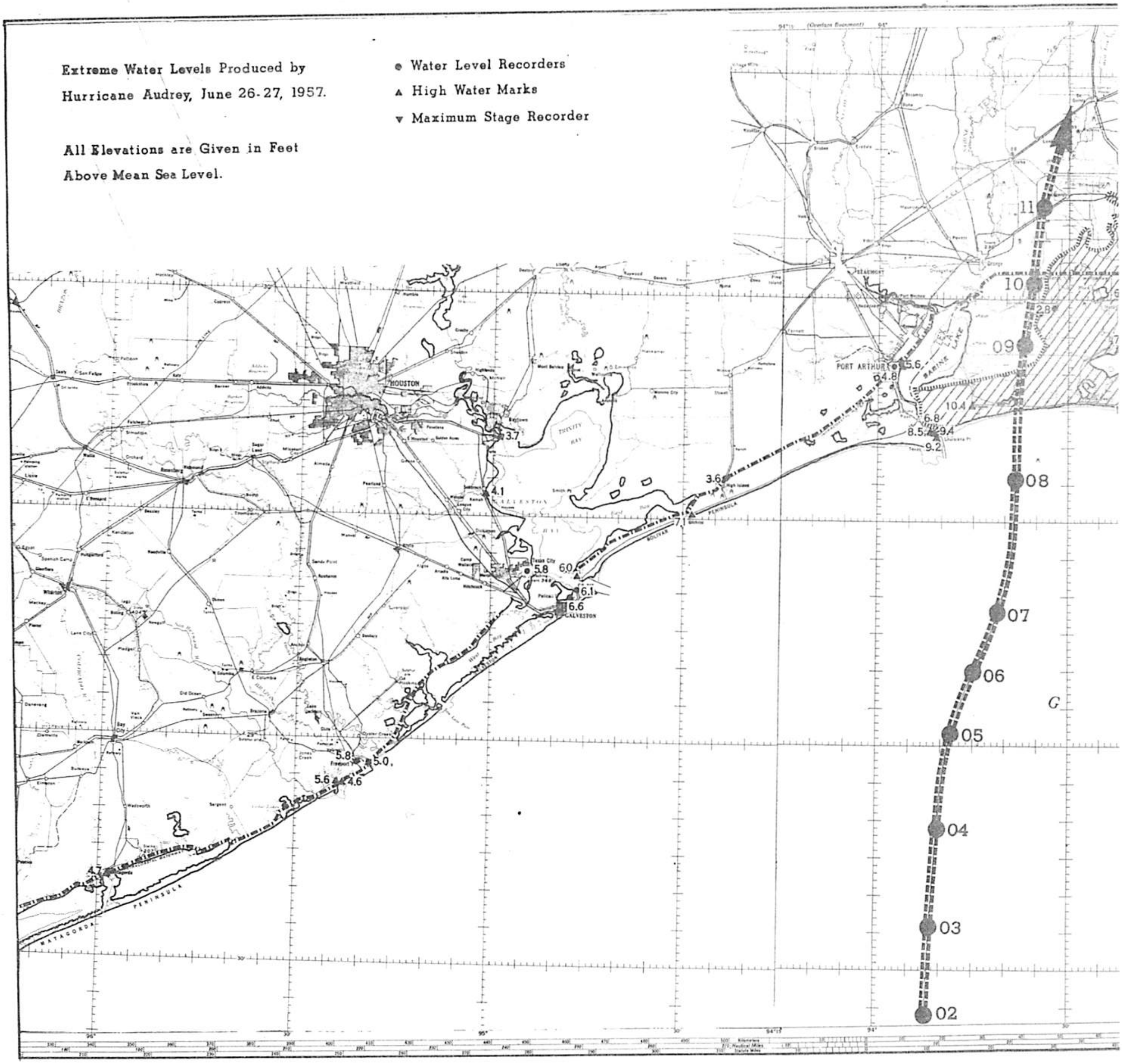
location on the map of the Louisiana and Texas
. Hourly positions of hurricane Audrey are



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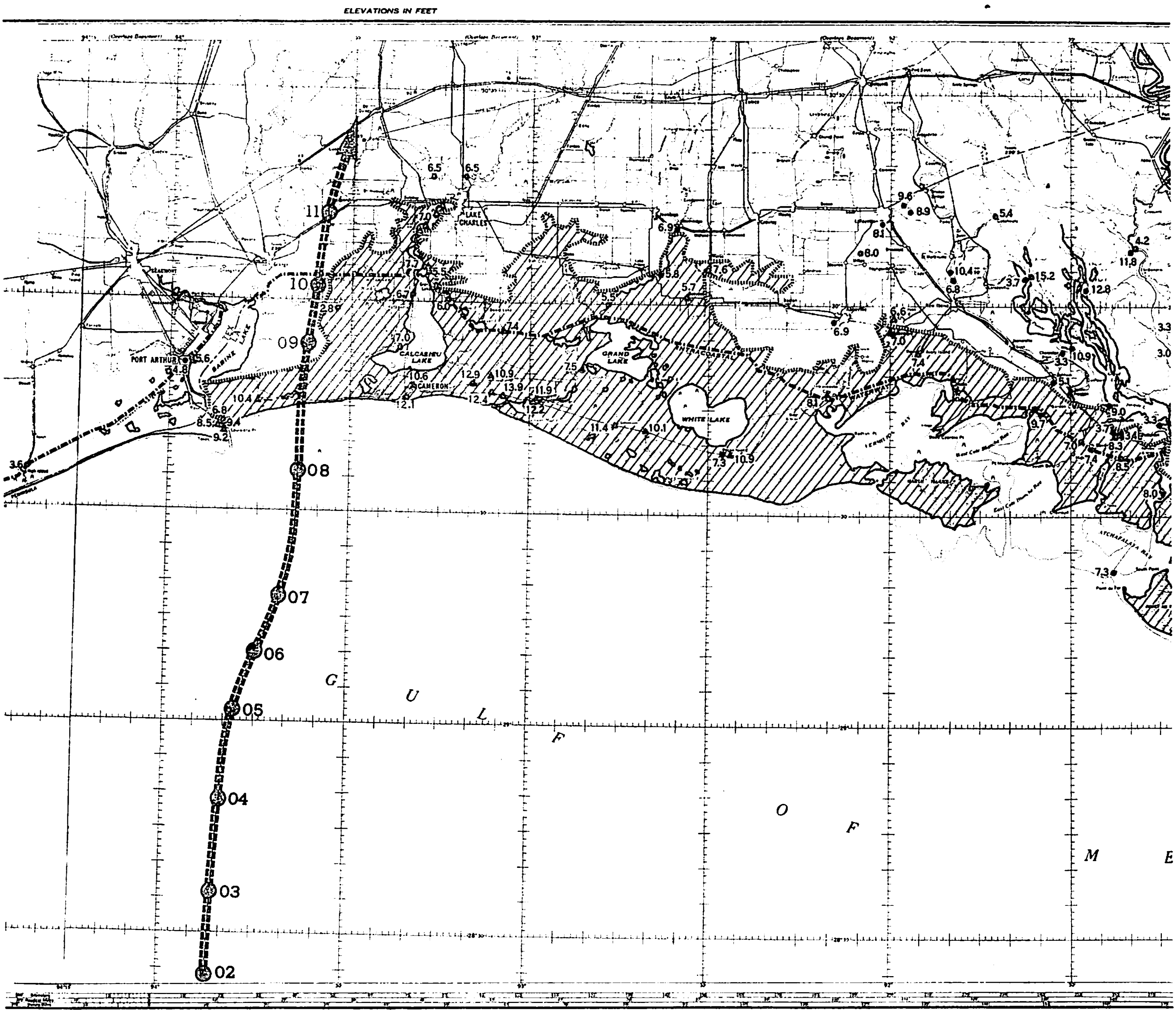
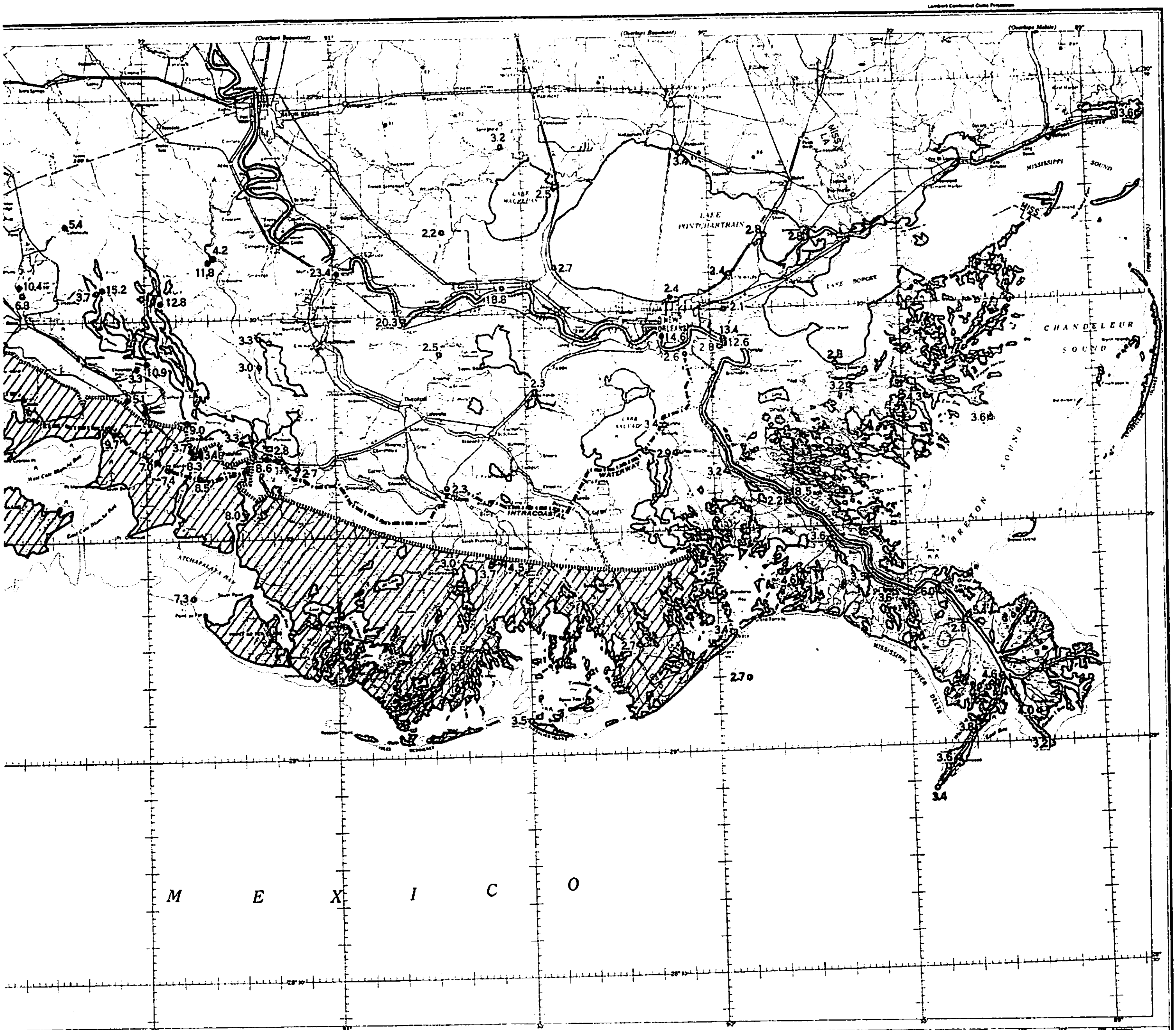


Figure 2. - Extreme tide elevations at locations along the Louisiana-Texas coast, hurricane Audrey, 1957. Shading indicates limit of widespread inundation.



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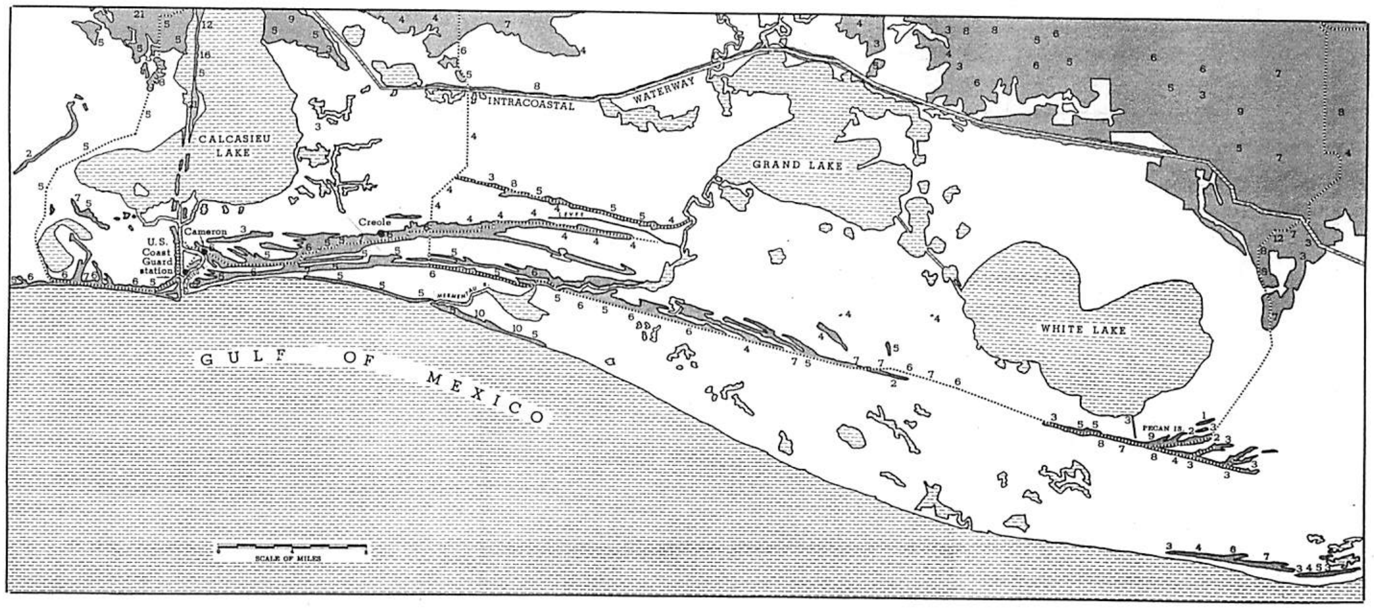

Figure 3. - Topographic features of region severely inundated during hurricane Audrey. Shaded areas are at least 1 ft. above sea level. Numbers give representative elevations along the narrow ridges.

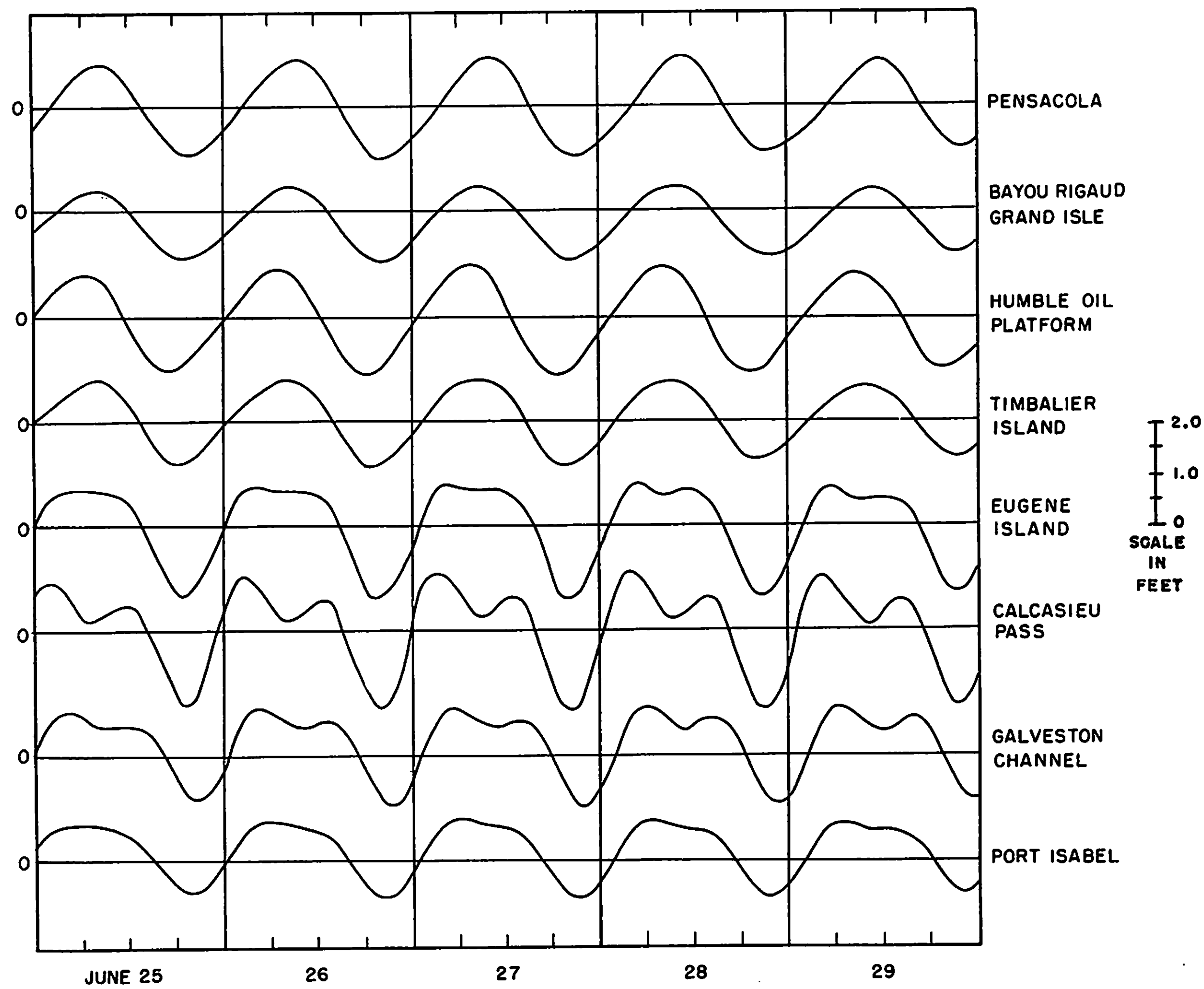

Figure 4. - Predicted tides for the period of hurricane Audrey.

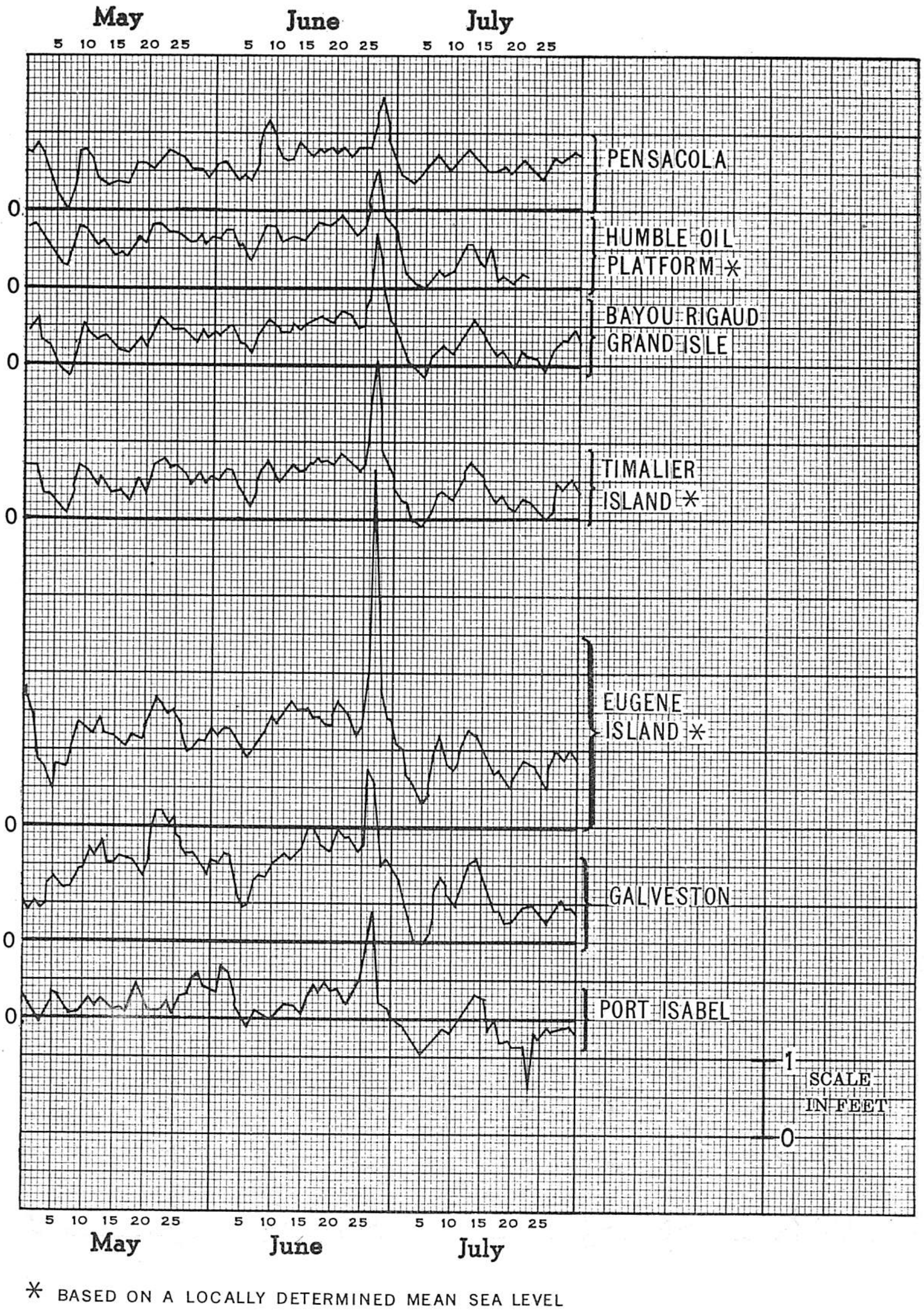

Figure 5. - Variation in daily mean sea level for May, June, and July of 1957 at several locations affected by hurricane Audrey.

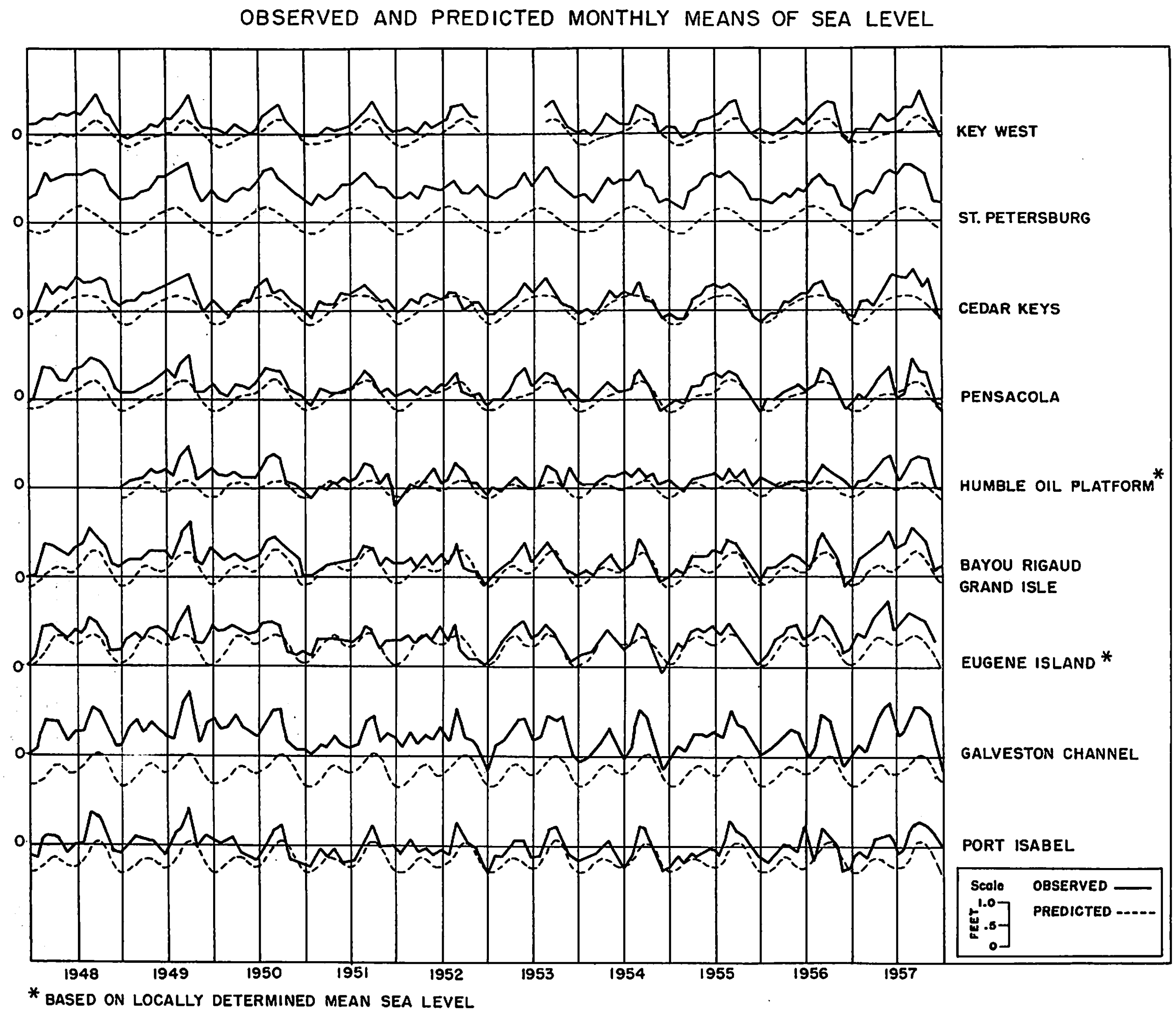

Figure 6. - Observed and predicted monthly means of sea level.

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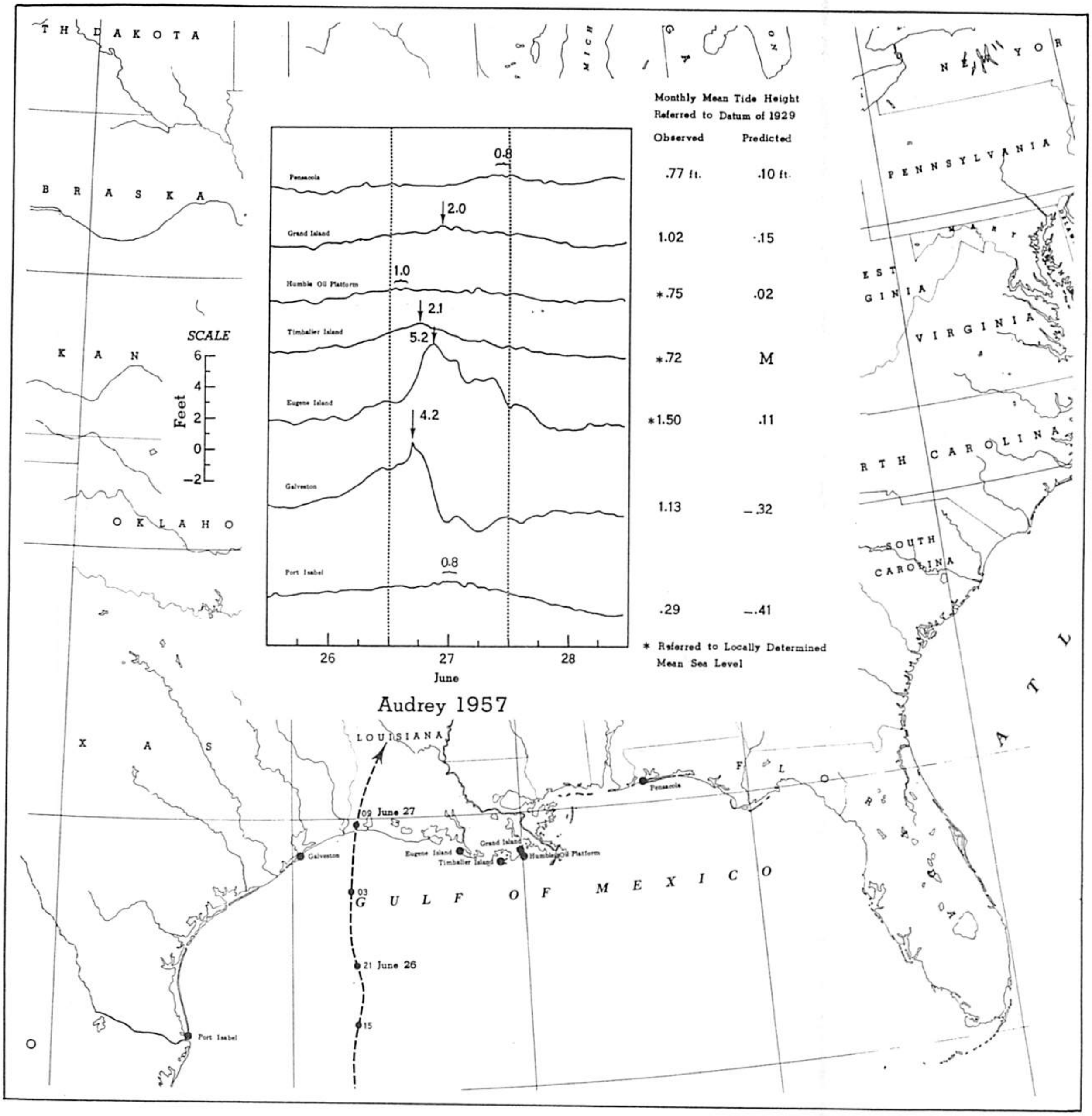


Figure 7. - Computed storm surge during hurricane Audrey plotted for those stations whose predicted tides are given in figure 4.

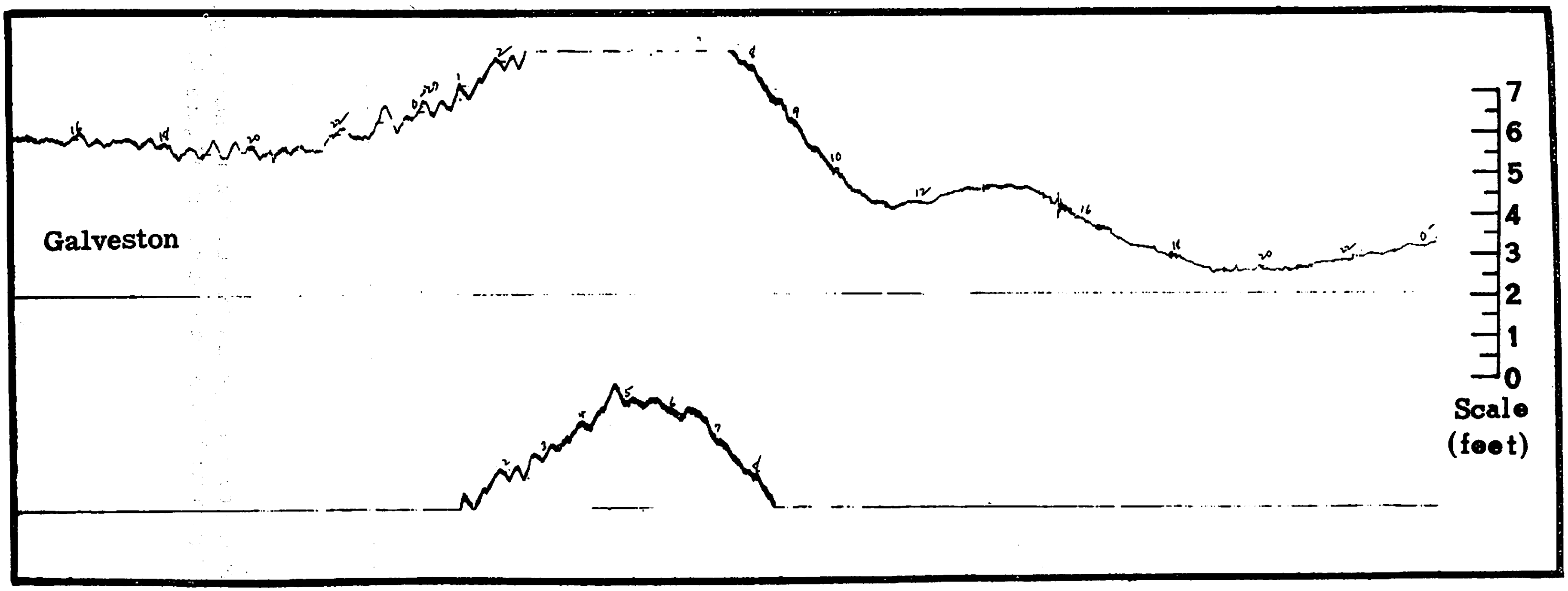
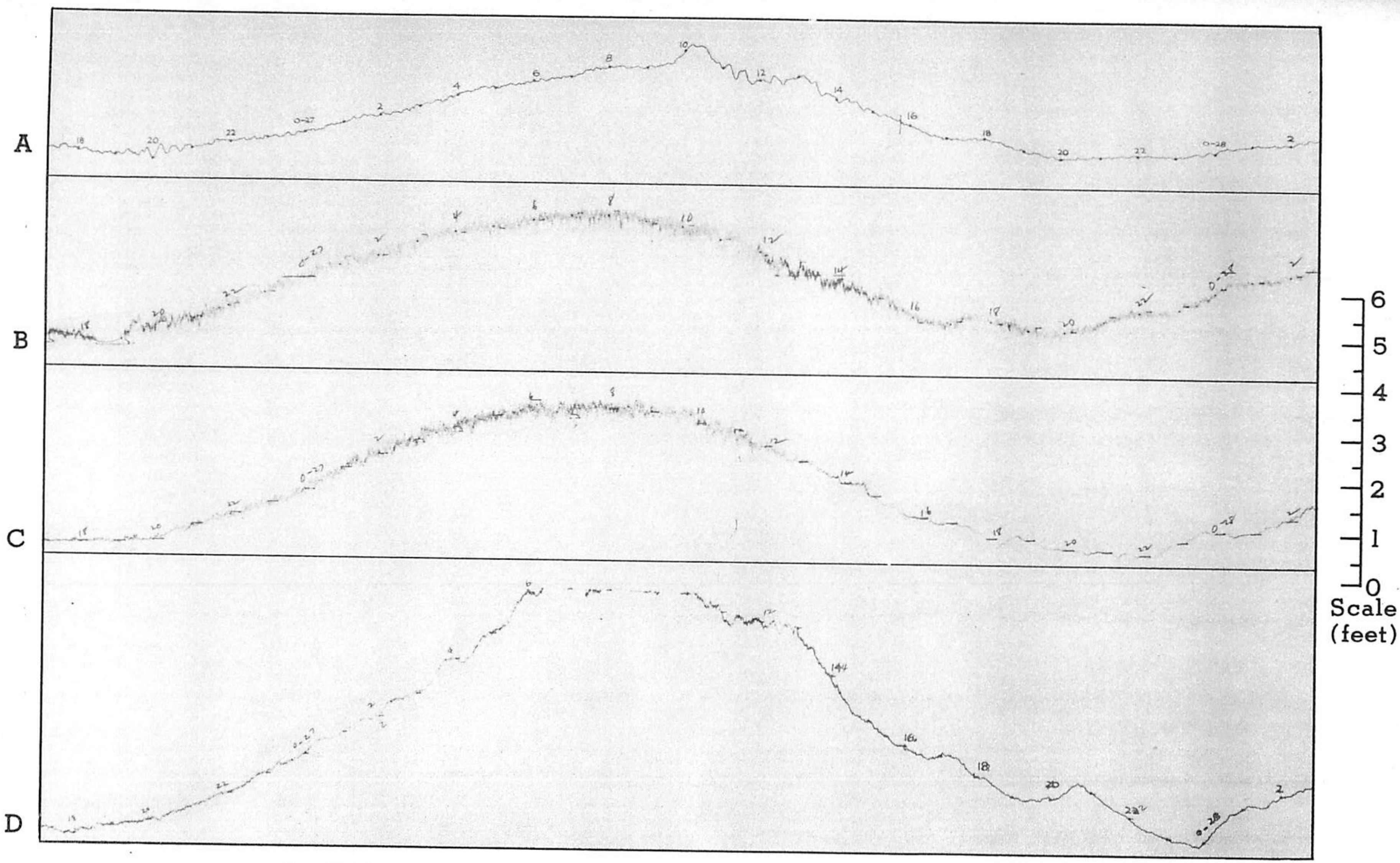


Figure 8. - Photograph of original Coast and Geodetic Survey tide gage record at Galveston.



A - GRAND ISLE
B - HUMBLE OIL PLATFORM
C - TIMBALIER ISLAND
D - EUGENE ISLAND

Figure 9. - Photo of records at four Louisiana tide gage stations.